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Second generation biofuels and bioinvasions: An evaluation of invasive risks and policy responses in the United States and Canada

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A B S T R A C T

Biofuels are being embraced worldwide as sustainable alternatives to fossil fuels, because of their potential to promote energy security and reduce greenhouse gas emissions, while providing opportunities for job creation and economic diversification. However, biofuel production also raises a number of environmental concerns. One of these is the risk of biological invasion, which is a key issue with second generation biofuel crops derived from fast-growing perennial grasses and woody plant species. Many of the most popular second generation crops proposed for cultivation in the U.S. and Canada are not native to North America, and some are known to be invasive. The development of a large-scale biofuel industry on the continent could lead to the widespread introduction, establishment, and spread of invasive plant species if invasive risks are not properly considered as part of biofuel policy. In this paper, we evaluate the risk of biological invasion posed by the emerging second generation biofuel industry in the U.S. and Canada by examining the invasive risk of candidate biofuel plant species, and reviewing existing biofuel policies to determine how well they address the issue of invasive species. We find that numerous potentially invasive plant species are being considered for biofuel production in the U.S. and Canada, yet invasive risk receives little to no attention in these countries' biofuel policies. We identify several barriers to integrating invasive species and biofuel policy, relating to policy analytical capacity, governance, and conflicting policy objectives. We recommend that governments act now, while the second generation biofuel industry is in its infancy, to develop robust and proactive policy addressing invasive risk. Policy options to minimize biological invasions include banning the use of known invasive plant species, ongoing monitoring of approved species, and use of buffer zones around cultivated areas.

Contents

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1. Introduction

In an era of rising oil prices and growing concerns over climate change, biofuels are receiving increasing attention from governments worldwide as alternatives to fossil fuels [1]. Unlike gasoline and diesel, biofuels (which are derived from biological material like carbohydrates and lipids) are renewable resources, and theoretically carbon-neutral, since greenhouse gases emitted when they are burned may be offset by those absorbed when growing biofuel crops [2,3]. Biofuels thus offer the promise of energy security, and reduced greenhouse gas emissions. Additionally, biofuels could create jobs and promote economic diversification, especially in rural areas [4]. As a result, many governments have enthusiastically supported the development of the biofuel industry in recent years through financial subsidies, regulatory mandates, and research [5,6].

The rush to embrace biofuels, however, may be premature and misguided. The strong desire to mitigate greenhouse gas emissions and strengthen energy security has meant that the environmental and socio-economic sustainability of biofuels has been subject to limited scrutiny [6–9][1] . Yet the large-scale production of biofuels required to shift from our current dependence on fossil fuels brings with it a suite of potential problems. For example, widespread conversion of forest, grasslands and peatlands to bioenergy plantations would lead to increased carbon emissions as a result of burning or decomposing biomass, and to loss of habitat and biodiversity [10]. Intensive agricultural practices could increase pollution, as well as soil erosion and depletion [11,12]. Furthermore, first generation liquid biofuels are derived from crops also used for animal or human food (e.g., canola, corn, soy, sunflower, sugarcane, oil palm and wheat) and thus can displace food production, driving up food prices and exacerbating food insecurity [13–15].

Second generation biofuels derived from ligno-cellulosic plant material (e.g., perennial rhizomatous grasses and woody plant species) are increasingly attractive to the biofuel industry because they are expected to be more efficient (i.e., have higher energy yields) than first generation crops and will not compete directly with food production [1,14][2]. However, many of the most popular second generation crop species are not native to North America, and some are known to be invasive (e.g., giant reed, *Arundo donax*; false flax, *Camelina sativa*) [16], raising the specter of the introduction and spread of invasive species across the continent (Table 1) [6,16]. Indeed, the sheer scale of biofuel cultivation envisioned worldwide (estimated to reach 1.5 billion ha by 2050, which would equal all agricultural areas now under production) will increase the propagule pressure of invasive plant crops, thereby boosting invasion success [8,17,18]. However, the risk of plant invasions and the subsequent potential for economic and ecological damage are rarely considered in the appraisal, development and regulation of different biofuel feedstocks [1,8–20].

An additional threat is posed by the development of genetically modified (GM) second generation feedstocks. At present no GM crops have been designed specifically for biofuel production worldwide [21], but modification of second generation plant species could prove desirable if it improves production and conversion processes (e.g., by increasing biomass yield and reducing lignin content respectively) [22]. Such introduced traits could make GM biofuel crops invasive, particularly if modified genes spread to native plant populations [23–25].

The second generation biofuel industry is still in its infancy in North America, as the commercialization of cellulosic feedstocks currently faces technological and financial barriers [15,26–29]. Nonetheless, several commercial-scale production plants are already under construction (e.g., biorefineries run by Blue Sugars, Dupont, POET, and ZeaChem in the United States) [30–33]. Governments in both the United States and Canada are supportive of the biofuel industry, and have been creating policy in recent years to promote its development. Yet a comprehensive review of the risk of biological invasion posed by this nascent North American second generation biofuel industry has not yet been undertaken. In this study we evaluate this invasive risk and our preparedness to address it in both the U.S. and Canada. We first identify the plant species proposed for use as second generation feedstocks, and review the scientific literature to assess which of them are considered invasive risks. We then review biofuel policies in the U.S. and Canada to determine whether and how they address the issue of invasive species. Next, we identify major barriers to the integration of biofuel and invasive species policies. We close by recommending steps to strengthen governmental responses to this important issue.

2. Biofuels and invasive species

Many of the traits that make ideal biofuel crops are common to invasive plants, including rapid growth, high yields, perennial growth form, adaptability to a variety of habitats and climatic conditions, and resistance to pathogen or insect pests [8,34]. In North America, a variety of grass and woody plant species are being touted as the next generation of plants for bioethanol and biodiesel production, even though they are considered invasive or potentially invasive (Table 1). The Global Invasive Species Programme (GISP), a partnership of leading international scientific and conservation organizations, identified 20 plant species that have been recommended for biofuel production in North America despite being known to be invasive either there or elsewhere [16]. These include non-native species, such as miscanthus (*Miscanthus spp.*; native to Asia) [19], false flax (native to central Europe) [35], and Chinese tallow tree (*Sapium sebiferum*; native to Asia) [36]. Plants native to regions of North America, such as switchgrass (*Panicum virgatum*; native to eastern North America), could also become invasive if cultivated beyond their range [19]. Switchgrass has broad environmental tolerances and is a fast-growing, highly productive species, making it a prime biofuel candidate [37].

The use of established invasive plants as sources of biofuel has also been proposed as a way to control their populations while taking pressure off agricultural land for bioenergy production [38]. For example, invasive plants such as purple loosestrife (*Lythrum salicaria*), European common reed (*Phragmites australis*) and reed canarygrass (*Phalaris arundinacea*) could be harvested from wetlands as part of habitat restoration efforts [38]. Similarly, the

[1] Although Ref. [9] does go into greater detail on the environmental and socio-economic sustainability of biofuels.

[2] Another potential feedstock is algae, considered a third generation biofuel. Since the focus of this paper is on second generation biofuels derived from ligno-cellulosic material, algae will not be evaluated here.

Table 1
Potential invasive risk of selected plant species proposed as second generation biofuel crops in North America.

Species	Common name(s)	Native range	Habitat type	Invasive traits	Invasive status	Invasive threat	Suitability for present Canadian climate	Reference
Arundo donax	Giant reed, elephant grass, wild cane	Eurasia	Wetlands and riparian areas	– rapid growth rate – vegetative propagation – tolerates disturbed sites and poor soils	– known invasive in United States	– outcompetes native plant species, clogs shorelines and stream channels – disrupts flood control – raises fire potential – reduces habitat for native wildlife	no	[34,36,124]
Camelina sativa	False flax, wild flax, camelina	central Europe, central Asia	Well-drained soils	– tolerates marginal habitats, cold temperatures, dry conditions	– known invasive in North America	– agricultural weed	western Canada	[35]
Lythrum salicaria	Purple loosestrife, spike loosestrife	Eurasia	Wetlands, riparian areas, fields, floodplains	– high yield – vegetative propagation – tolerates dry conditions	– known invasive in North America	– spreads over large areas, forming dense monocultures – outcompetes native plant species – reduces habitat for native plants and wildlife – may affect decomposition rates and nutrient cycling – reduces native biodiversity	across Canada	[125]
Miscanthus spp. (*Miscanthus x giganteus*, *M. sacchariflorus*, *M. sinensis*)	Chinese sliver grass, Amur Silvergrass, maiden grass, zebra grass	Eastern Asia	Well-drained soils	– rapid growth rate – vegetative propagation – wind-dispersed seeds – tolerates wide range of climatic conditions	– known invasive in North America	– spreads to roadsides and riparian areas – raises fire potential	southern Canada	[19,44]
Panicum virgatum	Switchgrass	Eastern United States, central America	Prairies and open areas	– broad environmental tolerances – rapid growth rate – high yield	– potential invasive	?	central and eastern Canada	[19,37,44]
Phalaris arundinacea	Reed canarygrass, swamp phalaris	Europe, Asia, North America	Wetlands	– high yield – tolerant of poor drainage and drought conditions	– known invasive in North America	– outcompetes native plant species – chokes streams and wetlands	across Canada	[44]
Phleum pratense	Common timothy, timothy grass	Europe	Fields, roadsides, disturbed areas, along waterways and meadows	– high yield – rapid growth rate – vegetative propagation	– known invasive in North America	– outcompetes native plant species – inhibits secondary succession through allelopathy – host for variety of plant diseases and nematodes that can spread to native species	across Canada	[126,127]
Pueraria montana	Kudzu	Eastern Asia	Open fields and forests	– rapid growth rate – vegetative propagation – tolerant of	– known invasive in North	– outcompetes native plant species – blankets hydro poles causing	southern Ontario	[44,128]

				disturbed areas	America	power outages		
Phragmites australis	European common reed, phragmites, common reed, giant reed grass	Eurasia	Wetlands and riparian areas	– high yield – vegetative propagation	– known invasive in North America	– outcompetes native plant species – reduces habitat for native wildlife	across southern Canada	[125]
Sapium sebiferum (synonym is *Triadica sebifera*)	Chinese tallow tree	Asia	Wetlands and riparian areas	– tolerates saline conditions, flooding and cold temperatures – high yield	– known invasive in United States	– outcompetes native species – toxic to cattle and humans	no	[44,129]

terrestrial invasive plant kudzu (*Pueraria montana*) would be an abundant biofuel feedstock in the south-eastern U.S., where it has infested many native habitats [39]. However, developing markets for these highly invasive plants could create a demand for them, thus contributing to their spread and negative impact on native ecosystems [40].

While research into the agronomic and economic feasibility of developing second generation biofuels continues apace, very limited assessment of their potential invasive risk is occurring in North America [18]. Indeed, most assessments overlook biodiversity impacts altogether, focusing instead on evaluating mitigation of greenhouse gases and energy efficiency [13,41]. Furthermore, of the few studies that address invasive impacts, the majority examine biofuel cultivation in southern locales (e.g., California, Florida, Hawaii), with little attention given to possible invasive threats in more northerly locations, such as Canada.

Barney and DiTomaso [42] employed a weed risk assessment protocol to examine the invasive risk of three popular plants being considered by the biofuel industry: giant reed, giant miscanthus (*Miscanthus x giganteus*), and switchgrass. They found that giant reed had high invasive potential in Florida, where large plantations have been proposed [42]. Similarly, switchgrass had high invasive potential in California, unless sterile strains could be produced. Giant miscanthus, meanwhile, was found to have a very low chance of becoming invasive in the United States. Buddenhagen et al. [18] conducted a risk assessment of 40 biofuel plants proposed for use in Hawaii. The majority of species (70%) were found to be at high risk of invasion, compared with only 25% of non-biofuel plants. Similarly, a risk assessment of 12 plant taxa proposed for biofuel cultivation in Florida found that 58% of species had a high probability of becoming invasive in the state [43].

Barney and DiTomaso [37] used species distribution modeling to map areas presently suitable for switchgrass production and areas potentially vulnerable to invasion in North America under present and future climate scenarios. Currently suitable habitat is restricted mainly to within the plant's native range east of the Rockies. However, with climate change the northern extent of its range is predicted to expand farther into middle and northern latitudes of Canada. More recently, Barney and DiTomaso [44] carried out a global assessment of climate niche estimates of leading bioenergy crops. Current climatic conditions in Canada range from suitable to highly favorable for a number of known invasive biofuel candidate plants, including reed canarygrass, Amur silvergrass (*Miscanthus sacchariflorus*) and kudzu (Table 1).

A broader environmental impact assessment of the Canadian cellulosic ethanol industry indicated that production will likely be concentrated in the Prairie provinces, typically in rangeland habitat [41]. Introduced perennial grasses could become invasive in these areas, adversely affecting the diverse native plant communities that are characteristic of this grassland ecosystem [41].

3. Biofuel policies in the U.S. and Canada

Canada has lagged behind other countries in its development of a biofuel industry (e.g., Brazil, Sweden) [45,46]. Biofuel production has grown in the U.S. since the 1980s, but only since 2005 in Canada [5,47]. In both countries, the primary bioethanol feedstocks are first generation plant crops (mainly corn and wheat), while the primary biodiesel feedstocks are recycled cooking oil and animal fats [48,49]. Second generation feedstocks remain in the research and development phase [28,29,47]. The leading candidates for second generation crop commercialization include known or potential invasive species in North America, such as perennial grasses false flax, miscanthus, and switchgrass, and

non-native tree species such as Chinese tallow tree, poplar (*Populus* spp.) and willow (*Salix* spp.) (Table 1) [36,50,51].

The U.S. and Canadian governments have introduced numerous policies to stimulate the biofuel industry in recent years, including tax incentives, subsidies, funding for research and development, trade barriers, and renewable fuel blending mandates. Such policies have multiple, sometimes conflicting objectives, including carbon emissions reduction, energy independence, and rural economic development [52–54]. Expansion of biofuel crop production may enhance rural economic development but at the same time fail to reduce overall carbon emissions if it pushes biofuel or food crop production into previously uncultivated areas, if it is unaccompanied by measures to slow energy consumption growth, or if the chosen biofuels are actually net carbon emitting due to intensive fossil fuel use in the production process. Obversely, even if biofuel production enhances energy independence and reduces overall carbon emissions it may hinder rural economic development if it intensifies the growth of large-scale mechanized agriculture, increases food prices, exacerbates rural food insecurity, fails to produce a net increase in good rural jobs, or fails to slow the exodus of rural populations [53,54].

3.1. U.S. federal biofuel policy

In the U.S., the federal government plays a lead role in biofuel policy, due partly to its broad constitutional powers over energy, environment, and agriculture. Federal incentives for biofuel production have existed for decades, mainly benefiting the huge U.S. corn industry [55]. Corn ethanol production increased from approximately 662.4 million litre in the early 1980s to almost 25 billion litre in 2007, consuming one-third of the entire U.S. corn crop in 2008–09 [56]. In 2006 the U.S. government provided $6.7 billion to support the biofuel industry [57].

The two pillars of the current federal biofuel policy are the 2007 Energy Independence and Security Act (EISA) [58] and the 2008 Food, Conservation, and Energy Act (Farm Bill) [59]. The EISA strengthened the federal renewable fuel standard (RFS), changing its target from 28.3 billion litre of renewable fuel by 2012 [60] to 34 billion litre in 2008, rising to 136.3 billion litre in 2022 [61]. Starting in 2016, the entire increase (79.5 billion litre) must be achieved with “advanced” biofuels, including cellulosic biofuels and biodiesel [61,62], which would significantly increase the propagule pressure of invasive plants if they became a major component of second generation feedstocks. The EISA also established programs to fund biofuel research, development, commercial application, and infrastructure [61].

The Farm Bill created the Biomass Crop Assistance Program (BCAP), which aims to jump-start commercial-scale second generation biofuel production by paying 75% of the cost of establishing eligible crops and up to US $45/ton for delivering them to refineries [62]. Invasive plants and most food crops are ineligible for BCAP subsidies [51,53]. The Farm Bill also provides incentives for building advanced biofuel refineries, converting ethanol plants to renewable energy, producing non-corn starch biofuels, developing other products from biomass, and conducting biomass research and development [63].

President Obama added more fuel to the biomass fire by directing federal agencies to aggressively accelerate investment in and production of biofuels, establishing a Biofuels Interagency Working Group [64], and promoting marine and aviation biofuels [65]. Finally, the U.S. protects its domestic biofuel industry with substantial import duties on ethanol [49].

These policies appear to have spurred a massive surge in U.S. biofuel production, which rose from 15 billion litre in 2005 to almost 43 billion litre in 2009 [62].

3.2. Canadian biofuel policies

As in the U.S., Canadian biofuel policies take numerous forms, pursue potentially conflicting goals, and have mainly benefited growers of first generation biomass crops [48,66]. However, Canadian biofuel policy has lagged behind that of the U.S., due partly to the fragmentation of constitutional powers over energy, agriculture and environment between the federal and provincial governments, and partly to the economic and political importance of the petroleum industry as compared to the U.S., where the agricultural lobby is a more powerful counterweight to the oil and gas industry. As a result, the Canadian federal government is much less of a biofuel policy leader than its American counterpart.

Canada's federal renewable fuels strategy focuses on reducing greenhouse gas emissions while encouraging development of a domestic biofuel industry that will provide increased economic opportunities for agricultural producers and rural communities. As noted above, these goals of carbon emissions reduction and rural economic development are not well coordinated with each other, and potentially are in tension [53,54]. Moreover, the key elements of the strategy involve different government agencies with policy mandates that represent potential conflicts of interest between economic development, regulation and environmental protection enforcement (e.g., Agriculture and Agri-Food Canada, Environment Canada, Natural Resources Canada).

Since the 1990s, federal and provincial governments have supported biofuel production with modest tax breaks, grants, loans, and funding for research and development [48,67,68]. Several provinces have introduced renewable fuel mandates ranging from 5% to 8.5% ethanol in the gasoline pool and 2–5% renewable fuel in diesel and heating oil [66,68]. The federal government introduced a modest renewable fuel mandate in 2006, requiring 5% renewable content in the national gasoline pool by 2010, and 2% renewable content in the diesel and heating oil pool by 2011 [69]. Unlike both the American RFS and some provincial policies, none of the federal mandate must be met by second generation biofuels. In addition, various U.S. states and Canadian provinces have introduced low carbon fuel standards, intended partly to stimulate biofuel production [68].

The federal government's renewable fuels strategy also includes the CDN $1.5 billion ecoENERGY for Biofuels program, which provides production payments to ethanol and biodiesel producers; the CDN $200 million ecoAGRICULTURE Biofuels Capital Initiative, which subsidizes farmer-owned biofuel production facilities that use agricultural feedstocks; and the Biofuels Opportunities for Producers initiative, which subsidizes farmers to conduct biofuel feasibility studies and business proposals [49,69]. The fourth prong of the strategy—research, development, and commercialization—includes $500 million for private-sector development of second generation biofuels and $20 million for the Cellulosic Biofuel Network [66,68,69]. Finally, both federal and provincial governments maintain trade barriers to protect domestic producers, but these are modest compared to their American and European counterparts [49].

Partly in response to these policies, the Canadian biofuel industry invested $2.3 billion over 5 years to increase biofuel production, and by 2010 produced almost 2 billion litre annually [70]. Federal spending on biofuels is, however, less than a tenth of the U.S. federal spending [47] and shrank substantially after the election of the current government in 2006 [68].

4. Sustainability and invasive species in biofuel policies

The environmental and social impacts of biofuels have been recognized in both U.S. and Canadian government policies.

The sustainability of corn ethanol has long been controversial, given that corn is among the most energy-, water-, pesticide- and fertilizer-intensive crops, is planted in large-scale monocultures, and its use for fuel can displace food production [56]. In recent years biofuel policies have expanded from a narrow focus on greenhouse gas emission reductions to a broader preoccupation with environmental, social and economic sustainability [71–73]. The potential threat of invasive plants in the biofuel industry, however, has received little attention in the U.S. and even less in Canada.

4.1. United States

In the U.S., the EISA's RFS2 imposes some environmental conservation requirements on the sourcing of renewable fuels, including a prohibition against converting non-agricultural land to biofuel feedstock production and against harvesting biomass from old growth and late succession forests, as well as forests with rare or imperiled ecological communities [53]. The BCAP also has numerous environmental provisions, including requiring producers to implement conservation or forest stewardship plans and prohibiting biomass cropping on wetlands, grassland reserves, conservation lands, and non-agricultural land with native vegetation [74].

Invasiveness likely will become a contentious issue in the U.S. as biomass cropping intensifies, particularly if genetically modified plant varieties are introduced [53]. Yet federal biofuel policy says very little about invasive species and a great deal about aggressively increasing biomass feedstock production. As a result, some commentators believe biofuel policy is at odds with a 1999 Executive Order issued by President Clinton, which requires all federal agencies to ensure that their activities do not cause or promote the introduction or spread of invasive species [8,19,75].

U.S. federal biofuel policies address invasive species in three ways. First, biofuel crops that are or have the potential to become noxious or invasive are ineligible for BCAP subsidies [53]. Second, while the EISA does not explicitly rule out invasive species under the RFS2, it requires the U.S. Environmental Protection Agency (EPA) to assess and report to Congress every 3 years on the impacts of RFS2 on—among other things—the "growth and use of cultivated invasive or noxious plants and their impacts on the environment and agriculture" [29,58]. These two provisions, if implemented conscientiously, will help channel increasing attention and resources to the study of the potential invasiveness of new biofuel crop species. The third provision, on the other hand, is aimed at supporting efforts to combat existing invaders. It makes invasive plant material harvested from public lands in control or eradication efforts an eligible feedstock for purposes of the BCAP [76]. Similarly, salt cedar (*Tamarix ramosissima*), an invasive tree species which affects ecosystem services [25], qualifies as renewable biomass in New Mexico when removed through eradication programs from river basins and watersheds [77].

In 2011 the EPA released its first report on invasiveness and environmental impacts of biofuels [29]. The report examined the invasive threat of seven feedstocks: the two most widely used (corn and soybeans), plus five others (corn residue, perennial grasses, woody biomass, algae and waste materials). It concluded that corn and soybeans pose negligible invasive risks, but that extensive use of the herbicide glyphosate with genetically modified, glyphosate resistant ("Roundup Ready") strains of these crops might have indirect effects on invasive plants, increasing their glyphosate resistance and prompting the use of more toxic herbicides [29]. Meanwhile, the report characterized the invasion risk of some perennial grasses as low (e.g., giant miscanthus), some as potentially significant (e.g., switchgrass in some regions, and miscanthus varieties), others as clearly high (e.g., giant reed), and yet others as unknown but potentially high (e.g., future improved varieties bred for rapid and dense growth and tolerance to low soil fertility). It also noted outcrossing with compatible wild plants and dispersal of reproductive parts during transportation as potential ways for some of these crops to escape cultivation [29]. Options recommended to minimize invasion potential include avoiding the use of known invasive varieties (as in the BCAP), breeding for traits that reduce invasion risk (e.g., sterility), cleaning harvesting and transportation equipment, and establishing early detection and rapid response strategies [29]. Yet, paradoxically, the EPA has recently proposed that two invasive grasses, giant reed and napier grass (*Pennisetum purpureum*) qualify as advanced biofuel feedstocks under the RFS2 [78].

The report warned that woody biofuel species could also become invasive, though likely over much longer time scales. It noted the unknown risks associated with future improved woody feedstocks, including invasion and transfer of novel traits to wild populations. On the other hand, the report characterized the invasion risk of forest residue removal as negligible. Recommended risk mitigation strategies include planting native species or sterile hybrids, avoiding species that were invasive elsewhere or have high growth rates, and (in the case of potentially invasive species) maintaining buffer zones and harvesting before seed maturation [29].

The analyses and conclusions of the report were preliminary, speculative, and limited by pervasive uncertainties and knowledge gaps. Nonetheless, it offers useful guidance and serves as a benchmark for continual improvement of knowledge and best practices on biofuels and invasive species. It remains to be seen whether the concerns and recommendations raised in the report will be incorporated in a systematic way into U.S. federal policy on biofuels.

4.2. Canada

In Canada, discussion of the invasion risk of second generation feedstocks is virtually absent from existing policy discourse. There is no mention of the issue in the federal renewable fuels strategy, despite its emphasis on research, development, and promotion of second generation biofuels [79]. Instead, only general statements on the need to protect biodiversity, ecosystems, and natural resources, appear in the federal government's Guiding Principles for Sustainable Biofuels in Canada, which were developed in collaboration with industry stakeholders and provincial government partners [79]. Bill C-33, which laid the legislative groundwork for the current federal government's biofuel strategy, includes the provision for a periodic comprehensive review of environmental and economic aspects of biofuel production in Canada. The Act recommends that this assessment occurs every 2 years; however it is not mandatory. The first such review is expected in March 2013 [80].

The Canadian Food Inspection Agency (CFIA) is the federal agency responsible for monitoring and controlling the introduction and spread of invasive plants in Canada. Using pest risk analyses, the CFIA designates invasive plants as pests and/or noxious weeds, and regulates their entry and domestic movement through a variety of regulatory tools, including complete prohibition, import permits, phytosanitary certificates, quarantines, and destruction. As of April 2012, no proposed biofuel plant species are listed on CFIA's Pests Regulated by Canada List [81] although kudzu is recognized under the agency's Least Wanted Invasive Plants Project [82]. A search for the term "biofuel" on the CFIA website[3] produced only three unique results, of which just one discussed invasion-related risks of a proposed biofuel crop

[3] Conducted in August 2012.

Table 2
IUCN Guidelines for governments to mitigate the impacts of invasive species along the biofuel supply chain [102].

Stage in biofuel supply chain	Recommendations for governments
1. Selection of biofuel feedstocks and locations for plantations	– conduct a strategic environmental assessment at the national scale to identify appropriate biofuel crop species and plantation zoning practices – design quarantine efforts that reduce not only the threat of invasive biofuel plant species, but also any associated pest species and diseases – monitor the biofuel industry to ensure international regulations for species introductions are complied with
2. Importation of feedstocks/propagules into new ecosystem or country	– develop and strengthen quarantine regulations so they are based on sound ecological principles (e.g., adopt risk assessment process based on ecosystem approach) – allocate sufficient resources for monitoring and enforcement
3. Feedstock production	– develop 'polluter pays' regulations so that those responsible for the negligent release and spread of invasive feedstocks compensate those affected
4. Harvesting, processing, transportation and trade of feedstocks	– promote value-added projects that convert feedstocks at or close to the production site, to reduce the risks of propagules being moved over large distances – ensure quarantine procedures monitor movement of high-risk feedstocks nationally – develop communication and education programs for transport companies and other relevant stakeholders on the risks of biological invasions and importance of monitoring

(false flax), in the context of an application for a "plant with novel traits" approval [83].[4] A search of the entire Government of Canada website for documents containing the terms "biofuel" and "invasive" produced similarly meager results. Of 25 total results (including several comprehensive research reports and strategic action plans by Agriculture and Agri-Food Canada, the lead federal agency for biofuels), only two mentioned the connection between biofuels and invasive species, and then only in passing: the Parliamentary debates on Bill C-33 [86], and a magazine article on biofuels from algae [87].

5. Working toward effective policy on biofuels and invasive plants

The absence of a coordinated and comprehensive policy framework to address the invasive risk of biofuels in the U.S. and Canada highlights a serious gap in the development of a sustainable renewable energy industry. Calls for policy interventions to accelerate the transition to second generation biofuels tend to overlook completely the issue of bioinvasion e.g., [27]. The growing urgency to move away from a fossil-fuel economy is overshadowing the need to adopt a precautionary approach to biofuel development, which would consider potentially long-term and severe environmental threats presented by second generation feedstocks [88]. Clearly, potential environmental impacts of the emerging bioenergy sector carry little economic or political weight when compared with the immediate and pressing issues of energy security and climate change [41],[5].

Yet, while concrete government policy on the issue remains elusive, the seriousness of the invasive problem is recognized in literature aimed at policy-makers and the biofuel industry e.g., [28,90,91]. It is also recognized in the American legal academic literature e.g., [53,54,56,71,92]).

Much of the academic commentary does little beyond identifying the problem; however some commentators offer policy prescriptions. For example, Pyke et al. [93] emphasized the need for integration of climate change policy with invasive species policy. They argued further that the development of such policies should consider interactions between invasive species and climate change, as well as situations where climate change policies could negatively affect invasive species management, and where synergies between climate change and invasive species management could strengthen policies [93]. Davis et al. [94] called for the urgent development of a robust approach to ecological risk assessment before second generation biofuel feedstocks are put into wide cultivation, and proposed a framework for such assessment.

In contrast, policy prescriptions are common in the legal literature on biofuels. Like Davis et al. [94], Endres [53] emphasized that robust, credible procedures to assess and manage invasion risks are essential if the mistrust and bitter battles over genetically modified crops are not to spill over to the bioenergy field. She also [53,72] emphasized the need for consistent biomass sustainability standards. Bluemel [95] agreed, adding that the first priority of such standards should be the protection of biodiversity through, for example, prevention of biological invasions. Colbran and Eide [92] proposed international standards to, among other things, avoid introducing non-native species that carry risks of invasion. Glassman [96] recommended amending international trade agreements to restrict trade in biofuels produced from species that are invasive in the cultivating country, although he recognized that this is likely to be resisted by India and China, where the non-native and potentially invasive physic nut (*Jatropha curcas*) is cultivated for biofuel production. Riley [97] urged governments to adopt consistent, comprehensive regulatory definitions of invasive species, and to apply these definitions equally to both "useful" (e.g., biofuel feedstocks) and unwanted species.

Ongoing debate exists in the literature regarding the best policy for an emerging cellulosic biofuel industry [98]. Proponents of prohibition argue that a ban represents the most effective way to minimize invasive risks both from an ecological and economic perspective [99]. Once these crops are in cultivation, it will be extremely difficult to prevent escapes either through regulation or voluntary codes of practice, because large-scale monoculture plantations farmed over long periods will provide elevated opportunities for species to establish beyond cultivated areas [87].

[4] The other two results were the main database search page for Plants with Novel Traits [84] (listing "optimized biofuel production" as a novel trait) and an August 2012 discussion paper on modernizing Canada's livestock feed regulations, which mentions biofuels only once [85] (grain by-products of biofuel production as a source of ingredients for livestock feed).

[5] In Canada this is further underscored by the federal government's recent repeal of the *Canadian Environmental Assessment Act* and streamlining of the environmental impact assessment process. The intent of these changes is to avoid delays in economic development initiatives, confirming that economic considerations trump consideration of potentially harmful environmental impacts (see Ref. [89]).

Effective control and eradication measures will be severely limited (if not impossible), as well as costly and long-term [88]. Furthermore, application of the ‘polluter pays’ principle will be hampered by the escape-detection lag time inherent to biological invasions and the subsequent difficulty tracing escapes to a particular source [87]. However, others argue that there is little chance of banning invasive plants if they are viewed as economically important, and that mitigation of their negative effects may be the best option [41,100,101].

In addition, several prominent non-governmental organizations have published reports and guidelines on the issue. In 2008, the GISP recommended six steps to mitigate the risk of invasion by non-native biofuel crop species: (1) information gathering (check national noxious weeds lists to determine whether the plant has already been identified as invasive in the country where cultivation is proposed); (2) formal risk assessment to evaluate the feedstock species' invasion potential; (3) benefit-cost analysis to demonstrate real net benefits; (4) creation of incentives to select native or non-native species that pose the lowest risk to biodiversity; (5) risk management, including monitoring, viable controls, and contingency plans in the event of escape; and (6) evaluation of proposals according to sustainability criteria and/or certification schemes [16]. The report recommended that risk assessment, monitoring, and contingency planning should be mandatory in all cases and that known potentially invasive species should not be used in any biofuel production program [16].

In 2009, the International Union for the Conservation of Nature (IUCN) developed detailed guidelines on biofuels and invasive species specifically directed toward governments and industry (Table 2) [102]. The guidelines emphasized adopting a precautionary and proactive approach in the development of a biofuel industry, by, among other things, avoiding known invasive species, fully screening candidate species prior to introduction and use, and establishing a contingency fund to act as insurance against escapes (e.g., to be used for eradication, containment, management, and restoration). In addition, the IUCN recommended that governments develop an extended monitoring and assessment system beyond areas of biofuel cultivation, to provide ongoing surveillance at a landscape scale that would enable early detection of, and rapid response to, unforeseen biological invasions [102]. At the same time, the IUCN advocated for the use of the ‘polluter pays’ principle in the development of national biofuel strategies, in which governments would enact regulations requiring those responsible for the introduction and/or spread of invasive species within the biofuel industry to compensate those affected [102].

The U.S. Invasive Species Advisory Committee (ISAC), a group of non-governmental experts and stakeholders concerned with invasive issues, developed nine recommendations for federal government biofuel programs [103]. As a first step, ISAC recommended that the roles and responsibilities of all federal agencies involved with biofuel production be clearly identified and linked to efforts to minimize risk of spread and establishment of invasive crops (e.g., through cooperative networks, memoranda of understanding, communication forums etc.). ISAC also advocated for the promotion of biofuel crops not known to be invasive, or of low risk, and the adoption of risk assessment protocols to screen proposed crops within the industry. In addition, ISAC recommended that multi-year eradication plans based on integrated pest management be developed for all feedstocks prior to their use [103].

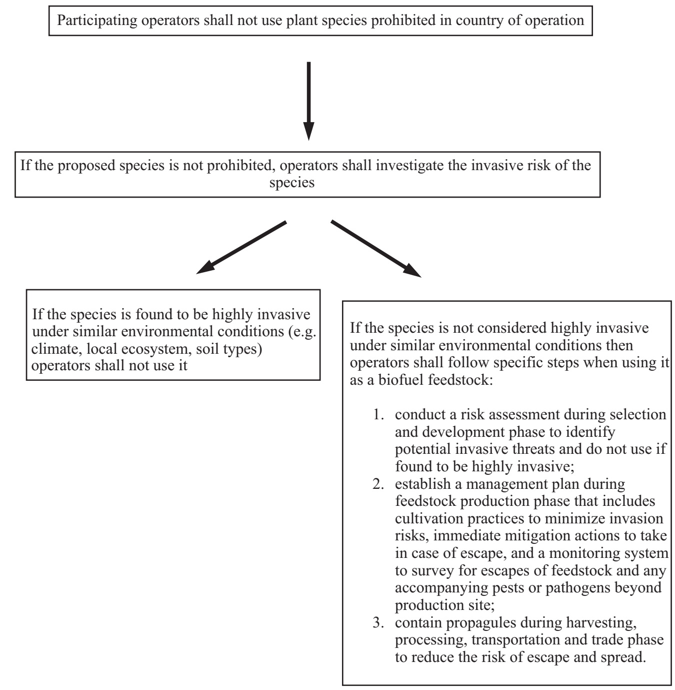


Fig. 1. Criteria developed by the Roundtable on Sustainable Biofuels (RSB) for biofuel producers and processors to prevent biological invasions from feedstocks [104].

Box 1–Selected areas of law relevant to bioenergy

- Land and water ownership, tenure and use rights;
- Land, forest and water management plans: harvesting plans and permits, plant breeding and cropping regulations, water resource allocation and abstraction laws;
- Air, ground and water pollution: greenhouse gas mitigation measures, compliance with pesticide and fertilizer use restrictions, waste management and disposal provisions;
- Environmental conservation: conformity with protected area and deforestation legislation;
- Protected species and habitats;
- Provisions on the use of genetically modified organisms;
- Environmental impact assessments;
- Social impact assessments: zoning, urban and rural planning considerations;
- Community participation: protection of indigenous peoples, local communities and women;
- Labor rights: minimum wage, job stability and the prohibition of child labor;
- Worker health and safety, in agriculture and in production facilities;
- Import and export laws;
- Price regulation of feedstock;
- Credit financing;
- Tax laws and other industry fee regulations;
- Product marketing and certification regulations; and
- Processing, sales, transportation and shipping laws

Source: [118].

Biofuel industry associations have begun to acknowledge some of these concerns. The international Roundtable on Sustainable Biofuels (RSB), a multi-stakeholder initiative that includes two Canadian biofuel industry representatives (the Canola Council of Canada and the Canadian Renewable Fuels Association), has developed a series of steps based on the IUCN guidelines to aid feedstock producers and processors to minimize the risk of invasive species being used in the industry (Fig. 1) [104]. The Roundtable seeks to use robust science in the development and implementation

of sustainable standards within the biofuel industry, and to monitor compliance through a third party accreditation system.

There is, in short, a growing body of policy analysis and prescription on biofuels and invasive species. Despite this progress, it appears that no country has formally adopted any of the aforementioned guidelines to minimize the invasive risk of second generation biofuels [105]. However, since 2011 the European Union (EU) has recognized the RSB framework as one of several voluntary schemes member states may use to ensure their biofuel supplies meet EU sustainability criteria [106]. Numerous barriers still exist, nonetheless, to closing the gap between the biofuels and invasive species policy domains.

6. Barriers to integrating invasive species into biofuel policies

6.1. *Policy analytical capacity*

Biofuel policy must be evidence-based if it is to minimize environmental risks such as invasive species. Evidence-based policy-making utilizes evidentiary or data-based decision-making so that government expectations reflect real conditions as much as possible [107]. The ability of policy developers to engage in evidence-based policy-making is influenced by their policy analytical capacity, or in other words, their capability to acquire and utilize knowledge effectively in the process of formulating policy [107]. Political analytical capacity is shaped by factors such as recognition of the importance of research, availability of qualified researchers and good quality data, opportunities for productive interdisciplinary interaction, and a culture that encourages transparency and risk-taking [107]. Although the policy analytical capacity of the Canadian federal government may be considered reasonably high, it is limited by insufficient vertical and horizontal coordination between government departments and organizations within and outside of government [107]. Such coordination is important to ensure that research being undertaken is relevant, timely, and utilized. Furthermore, recent federal government cuts to environmental spending, programs, staff and legislation (including termination of the Canadian Foundation for Climate and Atmospheric Sciences and the Invasive Alien Species Partnership Program), rival or exceed previous retrenchments in modern Canadian environmental policy, and will likely have a substantial negative effect on federal policy analytical capacity.

Policy analytical capacity also includes the ability to seek and utilize information produced by a variety of knowledge producers (e.g., governmental laboratories, universities, think tanks, among others). Based on a survey of Canadian provincial public servants, Howlett and Joshi-Koop [108] found that while policy analysts in the environmental policy sector have some interaction with those outside of their own jurisdictions, their particular training, employment patterns, and work activities mean they are unlikely to use knowledge drawn from external sources in their decision-making processes, thus limiting their ability to address complex interdisciplinary policy problems such as biofuels and invasive species [108].

Given the number of different policies affecting biofuels (e.g., agriculture, energy, environment, trade, transport, etc.; see Boxes 1 and 2 for a more exhaustive list) and the multiple levels of government involved in biofuel policy-making, effective policy analytical capacity will require significant horizontal communication between government agencies to coordinate policies, and minimize inconsistencies and oversight.

Box 2–Glossary of terms

Biodiesel: fuel derived from vegetable oils or animal fats produced when they are chemically reacted with an alcohol
Bioenergy: energy derived from non-fossil biomass that is used for heat, electrical power, or transport. Biofuels are a type of bioenergy.
Bioethanol: fuel derived from sugar or starch crops (e.g., sugar beet, sugarcane, corn, wheat), mainly produced through sugar fermentation (although a chemical process in which ethylene is reacted with steam may also be used)
Feedstock: a product used as the starting material to manufacture biofuels
First generation biofuels: use relatively simple and well-established technologies and food crops as feedstocks (e.g., maize, soybean, canola, wheat, sugar beets, sunflower)
Propagule pressure: a composite measure of the number of individuals of a species introduced combined with the number of introduction events
Second generation biofuels: use more advanced technology to extract and convert energy in cellulose using a wide range of perennial ligno-cellulosic feedstocks (e.g., fast-growing trees and grasses, and plant wastes)
Source: [6,34,130–132].

6.2. *Governance*

The multi-level federal systems of governance in the U.S. and Canada can promote policy innovation, dynamism and leadership, or conversely, they can result in buck-passing and deadlock [109,110]. The historical pattern of environmental federalism in Canada is characterized by long periods of policy stagnation punctuated by brief upward competition in the wake of environmental crises and heightened public awareness, followed by downward harmonization [109]. The limited and ambiguous character of the Canadian federal government's jurisdiction over issues such as environment, energy, biodiversity, and climate change may also inhibit federal policy leadership. But constitutional overlap and ambiguity only go so far in explaining the lack of policy progress or integration, and often may serve more as excuses for inaction than genuine barriers [111]. The structure of the Canadian political economy, including the persistent dominance of "old-economy" natural resource industries, is a more substantial obstacle to innovative environmental and energy policy [112,113].

Environmental governance often involves participation of actors from outside government in the decision-making process, yet the power to influence policy is not equitably distributed among these non-government actors [114]. In the case of biofuels, participants in the setting of regulatory standards include intergovernmental organizations, national and subnational governments, corporations, civil society organizations, and scientists [53,73]. Which actors influence government decisions depends on who the government views as salient and worthy of attention (e.g., which have the power to influence the decision-maker, which have legitimate claims, and which demonstrate urgency) [115]. As decision-makers are politicians, political values will moderate their perceptions of participants. Well-funded and well-organized interests, such as the petroleum, agribusiness and automotive industry lobbies, may have more influence over biofuel policy than do their poorer counterparts, such as environmental groups. This imbalance is exacerbated in the case of the current government of Canada, which has its political base in Alberta, home to Canada's oil industry, and in rural jurisdictions where many farmers stand to benefit from policies promoting

biofuels[6] . Biofuel policy thus may not consider aspects such as the environmental risk of invasive species if this risk is of little importance to the most powerful actors involved in decision-making.

Moreover, as long as the use and regulation of biofuels fits seamlessly within the dominant economic and institutional structures of fuel and transportation, biofuel policy development may reinforce institutional patterns and policies which deliver continued benefits, making it increasingly difficult over time to transform the pattern or select other policy options that may be more sustainable [116]. For example, low biofuel content regulations will not require the overhaul of transportation infrastructure or the car industry. Nor do they represent a significant threat to the energy industries, which continue to profit from current policy and institutional patterns. In contrast, if regulators were to consider policies requiring the use of electric cars as an alternative to current gasoline cars, there would have to be a complete transformation of transportation infrastructure, entailing high costs to car manufacturing industries and setbacks to current energy producers. Thus, alternative fuels might be locked out of global fuel/transportation “techno-institutional complexes” if they have different production, processing, transportation and storage needs than gasoline and biofuels [116]. Hence, stakeholders contesting the use of biofuels for their negative environmental and social impacts are limited by the path dependency of current policies, which produce increasing returns to current energy and car industries.

Lastly, further critical inquiry is needed to better understand the role of international environmental authority structures in biofuel governance and their impacts on national and regional policy [117]. For instance, although international agreements specifically addressing biofuels are still in the early stages of development (e.g., the proposed Canada–European Union Comprehensive Economic and Trade Agreement), several existing international environmental conventions and protocols impose obligations on member states to take regulatory measures to address climate change and encourage the promotion of legal frameworks for biofuels. Examples include the Vienna Convention for the Protection of the Ozone Layer, the Montreal Protocol on Ozone-Depleting Substances, the United Nations Framework Convention on Climate Change (UNFCCC), and the Kyoto Protocol and its eventual successor(s). Moreover, there have been three key international conferences with important implications for bioenergy regulation: the United Nations Conference on Environment and Development, Rio de Janeiro, 1992; the World Summit on Sustainable Development, Johannesburg, 2002; and the International Conference for Renewable Energies, Bonn, 2004. These conferences have motivated international action on bioenergy through the adoption of principles and other “soft law” measures as well as the implementation of binding international agreements stating environmental and sustainable development commitments [118]. In addition, two international environmental agreements impose binding commitments which must be taken into account by signatory countries seeking to promote the bioenergy sector: the Convention on Biological Diversity (CBD) and the UN Convention to Combat Desertification (UNCCD), which address environmental concerns over the production of bioenergy feedstocks in sensitive ecological areas. The CBD's scientific advisory body has warned of the potential adverse effects of biofuel production associated with uncontrolled introduction and spread of invasive species [119].

6.3. Conflicting policy objectives

As discussed in earlier sections, the U.S. and Canadian biofuel policies typically pursue multiple objectives of carbon emissions reduction, rural economic growth and energy independence. These goals may conflict with other policy objectives such as environmental protection, biodiversity conservation and food security [10–15]. They may also conflict with each other: biofuel crop production may enhance rural economic growth at the expense of reducing greenhouse gas emissions, or increase energy security without generating sustainable rural economic development [53,54]. The government agencies responsible for developing or implementing biofuel policies may have conflicting mandates, for example, environmental regulation versus agri-business promotion (see Section 3.2, above). Furthermore, the discretionary power of ministers and cabinets to approve development projects or overturn decisions made by environmental appeal boards tends to blur lines of accountability [120].

7. Conclusion

While there appears to be growing awareness in the academic scientific, policy and legal literature of the risk of invasion from biofuel crop development, government policy in North America lags behind, particularly in Canada, where we found only passing mention of biofuels in connection with invasives, and where there is only non-mandatory provision for review of environmental and economic impacts in the federal biofuels strategy. The concern over invasive biofuel crops is apparent in the emerging debate over whether to ban entirely the cultivation of potentially invasive cellulosic biofuel species [87,98] or simply mitigate their risks [41,100,101]. This debate may not be easily resolved given its tension between the need to avoid a growing legacy of invasive species impacts on one hand, and the need to mitigate climate change impacts on the other.

Commercialization of second generation biofuel crops is in its early stages in the U.S. and Canada, giving governments the opportunity to develop and implement effective biofuel strategies before widespread production begins. But time is limited since companies are already experimenting with the conversion of potentially invasive feedstocks into cellulosic ethanol. In Tennessee, for example, a demonstration biorefinery jointly run by DuPont and Genera Energy is currently evaluating the use of switchgrass for commercial production [121]. While switchgrass is native to eastern North America, such an enterprise would be problematic if production were to extend into western North America.

Government should be actively involved in the formation and regulation of the industry, so that proper environmental assessment of proposed biofuel crops occurs well before significant investment and industry momentum to adopt them has taken place [122]. If the government fails to take on this regulatory role, invasive concerns will easily be trumped by economic interests [102]. Participation of biofuel researchers and invasion biologists will be critical to ensure that policy is based on sound scientific principles, such as what traits to avoid in breeding programs and what criteria to use in risk assessment programs (e.g., Australia's Weed Risk Assessment system has successfully been adapted for use in several geographic regions worldwide to evaluate invasive risk of proposed biofuel plants) [122].

If steps are taken early to identify and prioritize threats, invasive feedstocks can be avoided altogether, before a market is developed for them. This will require the development and coordination of databases indicating invasive risk of proposed crops worldwide, and their suitability for cultivation in Canada under current and future climate scenarios, which can be used to create a ‘white list’ of plant species deemed low risk, and thus acceptable for the Canadian biofuel industry [99]. Ongoing vigilance through pre-entry screening procedures and post-entry

[6] Although farmers may also experience negative impacts of biofuel feedstocks if they spread and damage other agricultural crops.

evaluation of all introduced crops will ensure that prohibited species do not sneak into the system, and that established crops are dealt with if they become invasive [20,123]. Any new feedstock approved for cultivation should initially be planted on a small-scale to monitor it for invasive tendencies, then scaled up if found to be acceptable [8].

Policymakers should also adopt an ecosystem approach, which considers the impacts of biofuel production within the broader landscape context [1]. For example, the spatial configuration of plantations needs to be addressed to minimize invasions into the surrounding landscape. Consequently, biofuel plantations should be planted away from riparian zones and degraded habitats, since these areas are highly susceptible to biological invasions [99]. The use of buffer zones around plantations, and the construction of processing facilities near to cultivated areas, would also reduce the risk of accidental spread of seeds and vegetative material [122]. An industry-wide levy to fund long-term monitoring and control of invasive biofuel plants could provide much needed support for the government's early detection and rapid response program [88]. Furthermore, creation of policy under an adaptive management framework will be critical for success because this approach promotes the regular revision and improvement of management plans, to incorporate best practices from around the world, as well as local knowledge, as this information becomes available [99]. Ultimately, government policy will also rely heavily on public support and acceptance, and thus a well-articulated public awareness campaign on the importance of prevention and control of invasive biofuels is crucial [88].

Governments worldwide seem committed to making biofuels a major energy source for the transportation sector, despite the questionable environmental and socio-economic benefits [8]. Global biofuel production has increased exponentially over the last decade, and conservative estimates are for production to double or triple over the next 10 years [100]. As momentum grows to develop this new bioenergy economy, it is incumbent on governments to incorporate wise policy addressing environmental concerns into the system. Canada has the opportunity to develop strong comprehensive policy on invasive biofuel crops before second generation crops come into use. But time is limited. If federal and provincial governments do not act soon, they will be faced with closing the barn door after the horse has bolted.

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